Synthetic Aperture Radar Imagery of the Ocean Surface During the Coastal Mixing and Optics Experiment

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Long-Term Goal

The long-term scientific goal of this effort is to understand the advantages and limitations involved in extracting quantitative information of oceanographic importance from Synthetic Aperture Radar (SAR) imagery of the ocean surface.

Scientific Objectives

The principal scientific objective of this investigation is to validate and improve our understanding of the physics that governs the imaging of oceanographic features such as internal waves and water-mass boundaries by microwave SAR. What makes this particular effort unique (and the chance of its success quite high) is the availability of a large number of SAR and Advanced Very High Resolution Radiometer (AVHRR) images supported by the concurrent *in situ* measurements collected as part of the Coastal Mixing and Optics (CMO) experiment. These measurements, which include density and current profiles along with the usual meteorological measurements, are precisely the ones needed to realize this objective. Moreover, this extensive data base should enable us to assess the usefulness of microwave and infrared satellite imagery as an applied tool to support and augment the objectives of CMO.

Approach

Our approach to the problem is to collect and archive as many SAR and AVHRR images as possible over the CMO experimental area; especially during the active phases of the experiment in August and September, 1996 and the mooring-recovery cruises in the summer of 1997. This imagery will then be correlated with the extensive *in situ* data collected during CMO along with that collected routinely from buoys as well as tide and meteorological stations in the area. We will use these *in situ* measurements to initialize our models that describe the surface-wave spectral modulation and the resulting variation in SAR backscattered power to validate and improve our understanding of the imaging physics.

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Work Completed

- Since August 1996, we have collected more than 20 RADARSAT and 11 ERS-2 images over the CMO experimental region. The RADARSAT imagery was made available to us as part of the Canadian Space Agency's Application Development and Research Opportunity program(ADRO). The ERS-2 imagery was also provided to us as part of a collaboration with Dr. Werner Alpers and Dr. Roland Romeiser of the Satellite Oceanography Group at the University of Hamburg. Software has been developed to read and manipulate the raw RADARSAT and ERS-2 image files accounting for the different formats of the two types of imagery.

- We have extracted "overview images" for each scene averaged to 1/12 the full pixel resolution (10 m for most of the RADARSAT imagery and 12.5 m for the remainder.) The location of the CMO sensor array and NDBC buoys is indicated on each image. Also, higher resolution imagery (1/4 full resolution) has been extracted for a roughly 42 x 45 km rectangular area centered on the CMO mooring array.

- AVHRR imagery corresponding as nearly as possible (within the constraints of local storms and cloud cover) to the time of the SAR overpasses has also been collected from our receiving station at JHU/APL and archived for comparison with the SAR imagery.

- A world-wide web page that highlights the SAR and AVHRR imagery collected over the CMO experimental area has been started. *In situ* data from sensors fielded as part of CMO as well as from standard sensors in the area such as the NDBC wind/wave buoys and NOAA tide gauges are also available on this web page. Furthermore, we are in the process of writing a brief description of our inferences about the local oceanography and meteorology based on comparisons and correlations among the *in situ* measurements and the imagery. Such descriptions are already available on-line for many of the scenes; especially the August-September 1996 RADARSAT overpasses. The address of our web site is: **http://fermi.jhuapl.edu/cmo/cmo_index.html**

Results

I. Wave-Current Interaction Processes:

Figure 1 shows a RADARSAT image of the CMO area collected during a descending overpass at 10:54 UT on 10 August, 1996. For this image, the Wide-1 beam mode, spanning an incidence-angle range from about 20° to 30° (from the right to the left hand side of the image), was used. The image dimensions are roughly 170 km by 180 km smoothed and sub-sampled to 120 m pixels. (The nominal intrinsic resolution of the 4-look RADARSAT imagery is about 25 m.) The region enclosed by the rectangular box (42 km by 45 km) in the lower left portion of the image indicates the area where four CMO mooring-arrays are located. Martha's Vineyard and Nantucket Islands are clearly seen at the top of the image (which is aligned at an angle of 12° east of North). At the position of the NDBC buoy 44008, shown near the right-hand (eastern) edge of the image, the measured wind at overpass time was about 3 m/s from the southwest. Signatures of internal-waves generated at the continental shelf break (to the southeast of the image) are visible all along the southern portion of the image including (weaker

signatures) in the CMO mooring area. These internal-wave signatures are produced by the interaction of the surface-wave field with the variable surface current induced by the orbital motion of the propagating internal-wave packets. The strength of the intensity modulation associated with these internal waves depends not only on the strength and direction of the induced surface-current field (aligned along the internal-wave propagation direction), but also on the wind and wave conditions. Using the *in situ* measurements from the CMO instrumentation as input, we plan to validate and improve our wave-current interaction and radar scattering models by comparing predictions of the intensity modulation with that measured from the imagery. (For a quantitative discussion of this wave-current interaction process, see e.g. [1] and references contained therein.)

Another example of a wave-current interaction process may be seen in the upper center of Figure 1 to the east of Nantucket Island. The narrow wave-like features are surface manifestations of tidal flow over the complicated bathymetry in the region of the Nantucket Shoals. Tidal flow over the strong bathymetry gradients cause a corresponding gradient in the horizontal surface current that in turn modulates the surface wave spectrum in the same manner as discussed in the previous paragraph in connection with internal waves. With our densely-sampled time series of SAR imagery, we have a unique opportunity to examine how the surface signature of the shoals changes as a function of the tidal phase.

II. Surface Waves Generated by Hurricane *Edouard*

During the last few days of August and the first few days of September 1996, Hurricane *Edouard* traveled north parallel to the east coast of the US reaching the vicinity of the CMO experimental area on 2 September, and then veered to the northeast into the North Atlantic where it eventually dissipated. We have three SAR images, on 30 August and 2 and 3 September, 1996, during the passage of *Edouard* near the CMO site that provide an excellent opportunity to study SAR imaging under high wind and wave conditions. As an example, we show in Figure 2 a RADARSAT image collected on 3 September, 1996 at 10:54 UT; about 36 hours after the closest approach of Hurricane *Edouard* to the CMO area. This image was collected 24 days after the image of Figure 1, and the imaging geometry is the same. The rectangle marks the position of the CMO moorings as before. At the time of the 3 September overpass, the wind speed as measured by the NDBC buoy, shown on the image in Figure 2 to the east of the CMO area, was about 8 m/s. Wind measurements at the CMO Met buoys showed the same magnitude.

To investigate the presence of surface waves generated by Hurricane *Edouard* in this overpass, we have generated a field of wave spectra by dividing the entire image into a set of sub-images. Localized spectra have been computed from each of these sub-images, and the resulting period and propagation direction for the dominant wave from each sub-image spectrum are displayed in Figure 3 . The length of the vector at each grid point in the figure is proportional to wave period and its orientation indicates propagation direction. (A 180° ambiguity in propagation direction, of course, remains.) The wave energy associated with each sub-spectrum is indicated in the figure by the gray-scale level of the arrow; white is high energy, black is low. Note that for spectra with smaller wave energy, for example in the eastern and southeastern portion of the image, two spectral peaks usually occur. This is because these spectra are so noisy that a clear single peak could not be identified. It is clear from Figure 3 that there is significant spatial variability in the estimated wave spectra as a function of position in the image. The area to the southwest of Nantucket Island in the vicinity of the CMO area (enclosed by the rectangle) shows significantly more spectral energy than the area in the southeastern corner of the image near buoy 44008.

The dominant wave period measured at this buoy however was about 10 s corresponding to roughly a 150 m for the dominant wavelength. This agrees with the wavelength derived from the spectra in the CMO region where the response is strong. In this region, the waves are coming from the northeast and were probably generated by Hurricane *Edouard* which was located to the southeast of Nova Scotia at overpass time. We have a potential explanation for the observed variability in the image spectra. In the east and southeastern portion of the imagery, the surface waves may be traveling primarily in the azimuth direction, and therefore not observable in the SAR imagery due to azimuth falloff [2]. The question then becomes: what causes the causes the rotation in propagation direction between the CMO area and the area near buoy 44008? Our present hypothesis is that wave refraction by the shallow bathymetry associated with Nantucket Shoals may be responsible for the change in propagation direction. We are currently attempting to substantiate this hypothesis using ray-trace techniques.

Impact/Application

We believe that our set of images collected in support of the CMO Experiment is unique among SAR data sets. We have in hand probably the most densely-sampled time series of satellite SAR imagery over a fixed oceanographic location yet to be collected. Moreover, almost every image in this time series is supported not only by nearly concurrent AVHRR imagery, but also by precisely the required *in situ* data necessary for quantitative interpretation and validation. During the next year, we will attempt to quantify our understanding of the various features in the imagery through precise comparisons between the measurements and model predictions. Success of this research should help advance the field of satellite oceanography toward the goal of extracting quantitative information of oceanographic importance from SAR imagery.

Related Projects

The work carried out as part of this grant compliments nicely the SAR wind extraction work funded by ONR and currently underway in our group at JHU/APL.

References

[1] Thompson, D.R., B.L. Gotwols and R.E. Sterner II, “A Comparison of Measured Surface-Wave Spectral Modulations with Predictions from a Wave-Current Interaction Model”, *Journal of Geophysical Research*, **93** No. C10, 12339-12343, 1988.

[2] Monaldo, F.M. and R.C. Beal, “Real-time observations of the southern ocean wave fields from the shuttle imaging radar”, *IEEE Trans. Geosci. Remote Sensing*, **33**, 924-949, 1995.

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Figure 1: RADARSAT image of CMO area collected from orbit 4000 on 10 August, 1996. In the lower center and right portions, one can see surface signatures of internal waves generated at the continental shelf break. At the upper right just east of Nantucket Island, backscatter modulation due to wave-current interaction effects produced by tidal flow over the Nantucket Shoals is clearly seen.

Figure 2: RADARSAT image of CMO area collected from orbit 4343 on 3 September, 1996 about 36 hours after Hurricane *Edouard* passed near the area. The wind speed measured at NDBC buoy 44008 was about 8 m/s; in agreement with that measured at the CMO mooring array. Surface signatures of tidal flow over the Nantucket Shoals can also be seen in the upper-center portion of the figure.

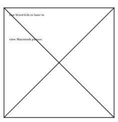

Figure 3: Estimated wave field from RADARSAT orbit 4343. The direction of the arrows at each grid point is the estimated wave direction (with a 180° ambiguity) and the length of the arrows is proportional to the wave period. The lighter-colored arrows represent higher-energy spectra; the darker arrows lower. The rectangular region shows the CMO experimental area (also shown in the SAR imagery). The NDBC buoy 44008 is also shown.